Building Technologies & Urban Systems Division
Energy Technologies Area
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Microgrids 2025 editorial

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Microgrids 2025 Editorial (v.4.2 - 7 Jan 25)

1. Introduction

We, the guest editors, thank everyone who has contributed to this virtual special issue (VSI), Microgrids 2025. Primarily, of course, we recognize the considerable effort by the authors of the approximately 350 overwhelmingly high-quality submissions received. Equally important though, are the (literally) thousands of reviewers involved in the process. Our sincere thanks to them, and self-evidently, this VSI would not exist without their contribution.

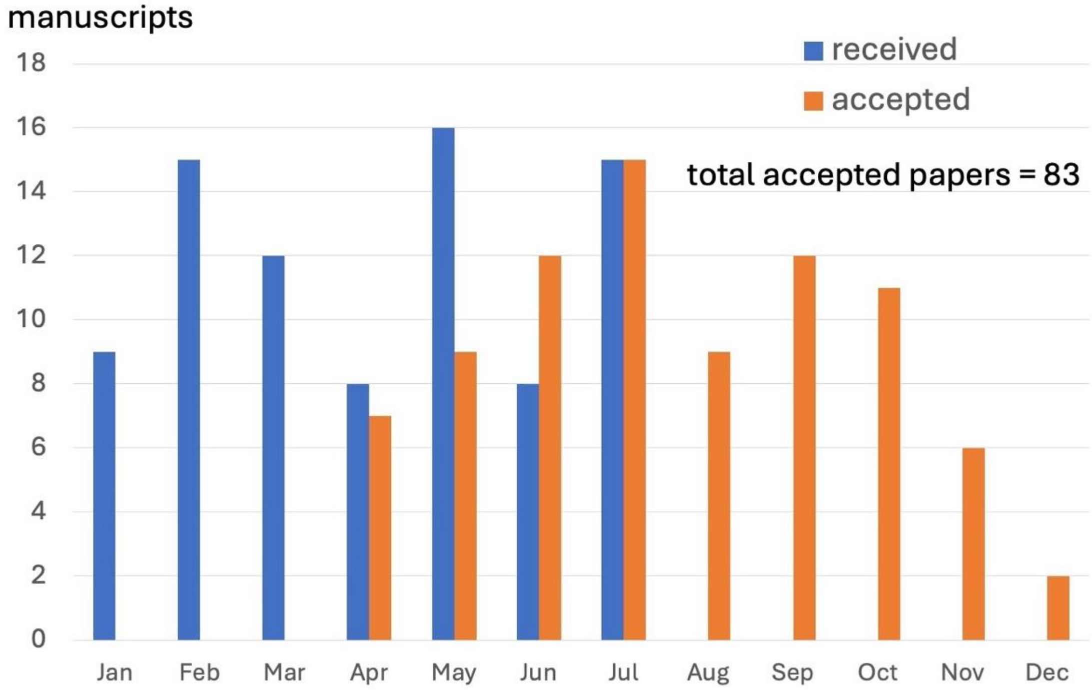

Figure 1. Monthly Manuscript Progress

Prior Applied Energy special issues on this topic concluded in 2021 and 2023, and this one follows the established pattern [1]. Microgrids 2025 was open for submissions from 1 January 2024 until 31 July 2024, and we have completed the review and processing over the entirety of 2024. Already in April, seven papers were accepted, and the last papers were resolved in December. Figure 1 shows the progression of manuscripts through 2024. Submissions were received throughout the open period with modest surges in February, May, and July. Acceptances are more normal shaped, peaking in July. All papers are now in their final form and available at the VSI website [2]. After independent review, we ultimately selected 83 for publication, just one short of the 84 papers accepted in 2023. We achieved a 24% acceptance rate overall, lower than the 27% result of 2023, but nonetheless far exceeding the typical rate for Applied Energy of about 15%.

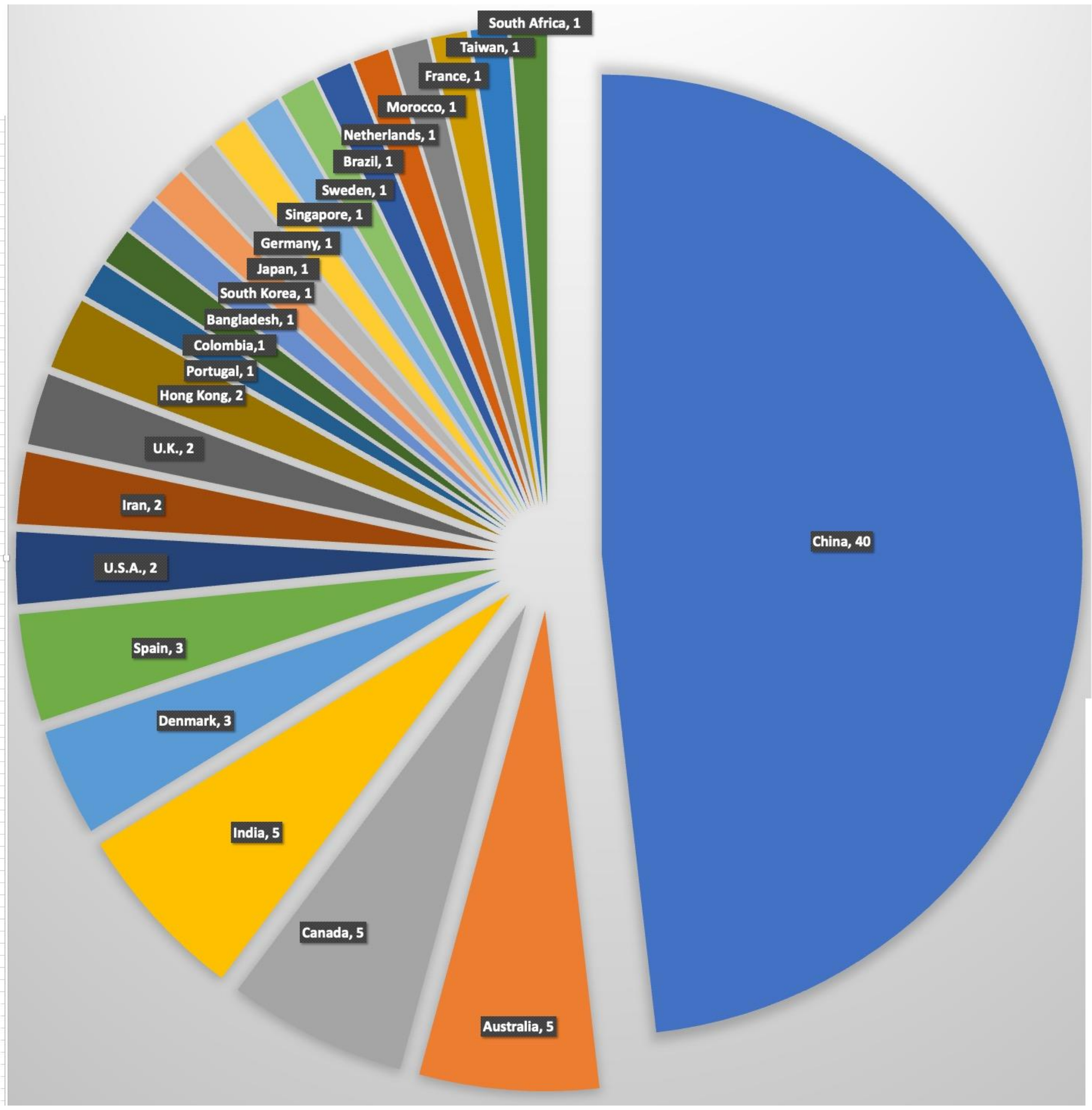

Figure 2. Papers by Lead Author Country and Region

We are again extremely pleased by the wide geographic dispersion of the submitted and accepted manuscript authors, with 24 lead-author countries and regions represented among the accepted papers, as shown in Figure 2. Further, additional countries are represented both in rejected manuscripts and by submission co-authors, since 121 papers were submitted by international teams. The total number of countries and regions involved reaches a remarkable 55! China dominates more than ever before with almost half of the accepted papers led by a Chinese author. Some other countries with strong showings are Australia, Canada, India, Denmark, and Spain. These results again confirm the global nature of the microgrid research endeavour.

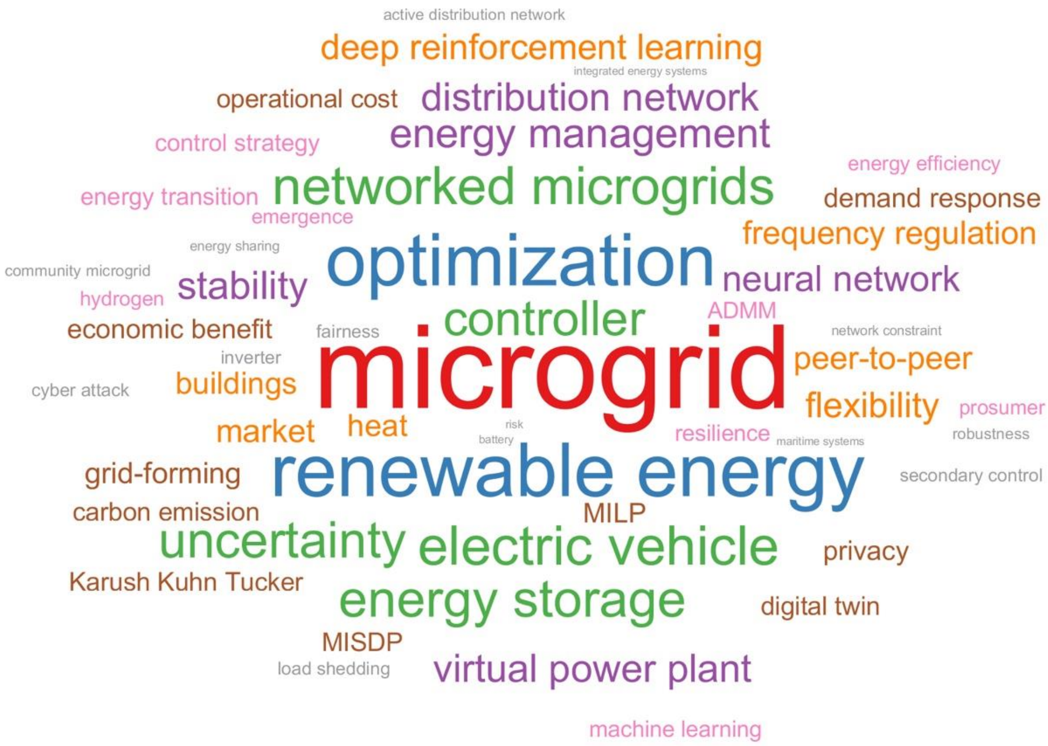

Figure 3. Word Cloud

The Word Cloud shown as Figure 3 above and the Co-Occurrence Network below were generated from the VOSviewer software package. The word cloud shows the approximate preponderance of keywords chosen by authors. The keywords were collected from accepted manuscripts and to some extent consolidated, then the cloud graphic showing keywords was generated by VOSviewer with font sizes proportional to occurrence. Generally, the topics covered have not changed much. Clearly from the figure, microgrid energy management systems continue attracting considerable attention, as do storage plus renewable energy (RE) generally, while many applications of optimization techniques continue to be popular. The key issues, such as, reliability, uncertainty, and resilience of power systems with high RE penetration remain key challenges, and transport electrification always plays a significant role.

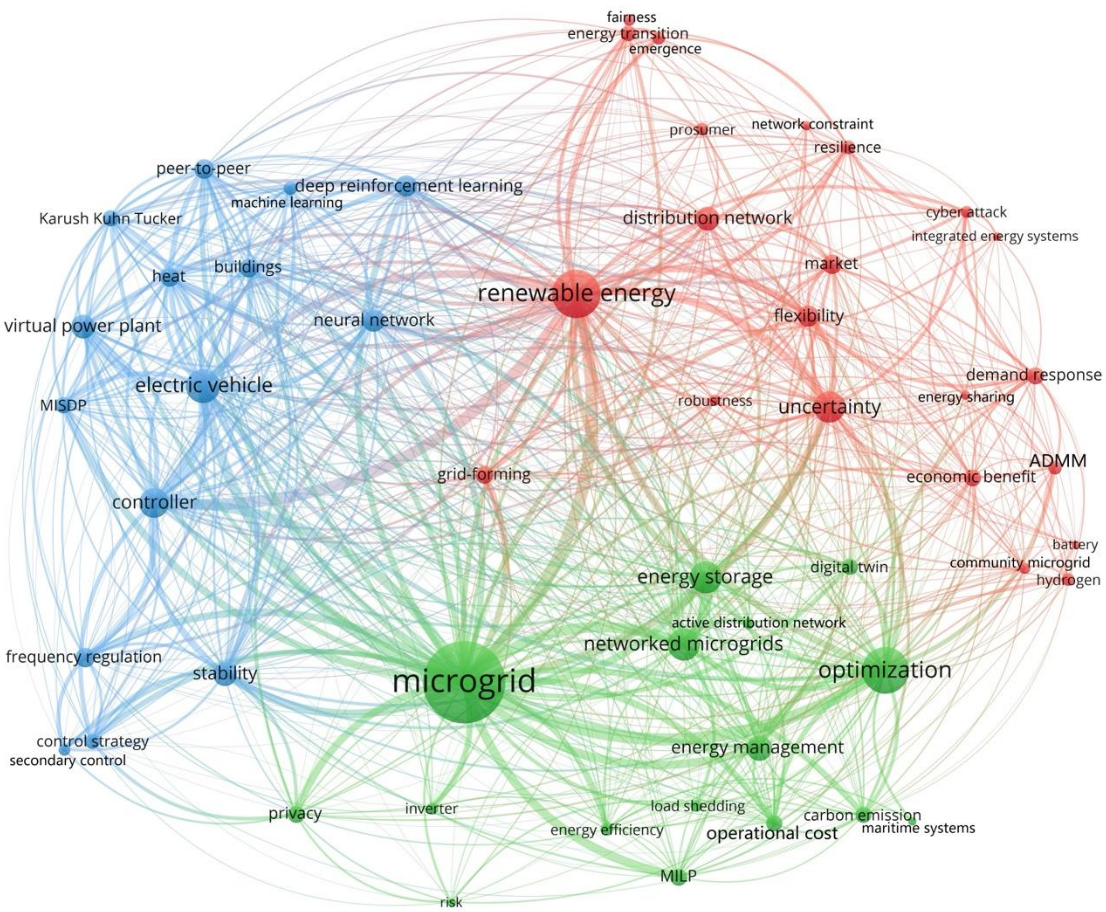

Figure 4. Co-Occurrence Network

In Figure 4, a co-occurrence network shows an analysis of the key content used by authors. A minimum of 5 occurrences of any keyword was set as the threshold for inclusion, leaving us with 53 keywords in the analysis shown below. The graphic shows a wide dispersal of keywords. While the research topics one would expect to see do generally show up, the areas of focus are broad and somewhat even. The strong red locus around the classic microgrid topics, RE, distribution networks, demand response etc., show they still command a healthy share of attention. And similarly, the blue one around control, electric vehicles, AI, etc. shows the ongoing importance of these technical problems. Representation of business models, market issues, etc. has weakened somewhat, while optimization applications are stronger than ever and networked microgrids is now established as a core topic. Overall however, we have generally failed in our efforts to attract submissions outside of hard analysis, although growing interest in the constructs of community energy systems has yielded some interesting softer papers.

Following is a brief blurb for each accepted paper, collected in five loose areas. The topics represented do not settle neatly into categories, so we apologize in advance to any authors who find their work is not correctly represented. Within each section, the paper order reflects the sequence in which the manuscripts were submitted.

2. Planning and Design

The following 15 papers address problems related to the planning and design of microgrids.

Seydali Ferahtia et al. [3] provide a review of the existing state-of-the-art (SotA) research in direct current (DC) microgrid development, relevant challenges related to security, communication, power quality, and operation, as well as the appropriate control and energy management strategies to handle them. Besides development, this paper offers a perspective on the application of control and energy management strategies for potential improvement of operating cost, emissions, and power system safety.

Mohammad Shaterabadi et al. [4] develop a multi-objective stochastic energy planning and management method for a power system comprising a microgrid, a nano-grid, and the main grid. The objective functions include microgrid profit, nano-grid cost, and total multilateral grid pollution. In addition, the impact of expanding H2 stations is discussed. Moreover, the effect of time-of-use (TOU) demand response (DR) programs according to the elasticity matrix (different operators and price-sensitive flexible loads) is investigated under diverse scenarios. The problem is modeled as a mixed integer linear program (MILP) and solved using the General Algebraic Modeling System (GAMS) and LP metric approach. Results from a typical study case show that by implementing the supposed planning, the microgrid's profit increases by about 22.53 $/day (10.8%), and the nano-grid's cost decreases by about 1.31 $/day (9.8%). The total environmental pollution is reduced significantly and reaches 1.06 kg/day.

Sujoy Barua et al. [5] present an optimization algorithm for the energy management of a RE solar/wind microgrid with multiple diesel generators applied to off-grid remote communities. The main objective aims to solve the economic emission dispatch problem to minimize energy costs and emissions. An enhanced metaheuristic optimization algorithm, the Lévy arithmetic algorithm, is applied and compared to other heuristic optimization algorithms showing improved performance. The enhanced optimization method using Lévy also provides good hourly cost results.

Yushu Pan et al. [6] propose an operation optimization and cost allocation strategy for a microgrid group with shared hybrid energy storage considering flexible ramping capacity. A multi-objective optimization model considering flexible ramping sufficiency and operating costs is constructed, and the range of uncertain variables is gauged by confidence intervals, which transform the model into confidence gap decision theory model. An improved Shapley method is used to construct the storage two-layer cost allocation model. Case study results show that total storage costs are reduced by 5.89% and ramping sufficiency is increased by 8.43% compared with a decentralized energy storage system, while the risk of power curtailment and load shedding is reduced at low additional cost.

Shuhan Li et al. [7] formulate dispatchable regions adapted to the variability of distributed RE generation in an alternating current (AC)–DC distribution network considering switchable devices, such as soft open points and reconfiguration with tie switches. It employs the outer polyhedral approximation and convex hull relaxation to approximate the original dispatchable region which is typically nonconvex with intractable 0boundaries. An efficient adaptive constraint generation algorithm is developed to search for boundaries of the approximated dispatchable region. Numerical results show the model can effectively adapt to the reconfigurable region with soft open points and verify the accuracy and computational efficiency of the proposed method.

L Ponnarasi et al. [8] deal with distributed state estimation-based centralized control design for internet of things (IoT)-enabled microgrid systems in the presence of deception attacks. The states of the microgrid are monitored by using a set of sensors linked through IoT-enabled networks, where attacks are presumed to occur during measurements. A resilient control algorithm based on distributed state estimation is developed, which uses only estimates generated by a certain group of IoT-enabled networked nodes. Subsequently, an augmented system is developed that incorporates both the microgrid system and the estimator error dynamics. The local and neighboring estimator-based control gains are designed using Lyapunov stability theory and matrix inequality. Simulation results demonstrate that the developed algorithm can estimate the state of the microgrid and controlling its operations, revealing that microgrids can provide a constant flow of electricity while being resistant to deception attacks and disruptions caused by the networks.

Pablo Calvo-Bascones and Francisco Martín-Martínez [9] deal with recommender systems that provide personalized advice based on data analytics and user preferences. They introduce two types of indicators, Flexible Consumption Indicators and Topology Indicators, with three main goals: to identify patterns of flexible consumption behavior using transparent and straightforward methods; to evaluate the feasibility of installing solar panels on building facades, rooftops, and structures; and to enhance understanding through a quantitative assessment of the feasibility and suitability of integrating RE sources, particularly photovoltaic (PV) systems. Actual consumption profiles and similar households' buildings 3D models are used to demonstrate the applicability of the proposed indicators. The study demonstrates how the proposed indicators can aid identifying users with flexible consumption profiles that reside in buildings compatible with RE sources.

Farid Moazzen and MJ Hossain [10] introduce a novel two-layer energy management strategy for microgrid clusters, utilizing demand-side flexibility and the capabilities of shared battery energy storage (BES) to minimize operational costs and emissions, while ensuring a spinning reserve within individual microgrids to prevent load-shedding. In the lower layer, the proposed approach devises optimal day-ahead operation policies, while the upper layer employs a cooperative strategy to further optimize operational efficiency across the entire cluster. The energy management problem is formulated as a mixed integer quadratic programming optimization. Real-world case studies show a reduction in operational costs for the base case scenario of 6.96 % compared to conventional microgrid management strategies and reduction of CO_2 emissions by up to 11.6 %, while improving system reliability.

Christina E Hoicka et al. [11] provide a preliminary investigation of “renewable energy clusters” and the factors that may predict their emergence. These clusters describe a range of place-based energy activities along the energy value chain, from production of technologies and innovations to their use. A qualitative approach is used to identify three initial types of RE energy clusters. Seven synthesised dimensions are used to typify and predict RE cluster emergence: actors, institutions, networks, knowledge and tools, proximity, location characteristics, and path dependency. These can guide the development of a sample of empirical cases of RE clusters that can be analysed through machine learning.

Zhang et al. [12] introduce a novel approach to energy system supply-demand optimization by simultaneous flexible energy-use regulation and microgrid operation scheduling, to explore human-centered multi-strategy parallel flexible energy-use regulations, and comprehensive evaluation parameters for energy supply-demand optimization. The study proposes adjustments of the start-up temperature of air conditioners, organized EV charging, light or plug management, and course optimization, while for microgrid optimization scheduling, novel objectives aimed at maximizing investment-environment-energy-society benefits are proposed. Results show that flexible energy-use regulation can reduce or shift 12.12% of energy demand during peak hours and 8.06% during the 17-19 h period. Regarding microgrid optimization scheduling, results showed 10.085%–11.728% of the annual average benefits in different cases, while the optimization integration of flexible energy-use regulations and microgrid operation scheduling yields 15.655%–18.016% of the annual average benefits.

Alejandro Valencia-Díaz et al. [13] present a two-stage stochastic mixed-integer nonlinear programming model, which is linearized to a MILP form, for optimizing the energy–water–carbon nexus in remote AC/DC microgrids aimed at sustainable community development. The model optimizes the selection, location, and operation of diesel generators, voltage source converters, PV systems, wind turbines, and BES systems while managing CO_2 emissions. The MILP model is implemented in GAMS and solved with C-PLEX, ensuring global optimization. Results show that integrating distributed energy resources (DER), compared to a case without these elements, reduces CO_2 emissions of the diesel generators and the operational costs of the energy–water–carbon nexus, highlighting the proposed approach's environmental and economic benefits.

Nirma Peter et al. [14] review the protection challenges posed by the integration of distributed RE sources on the low-voltage distribution grid through inverter protection challenges, including variations in short-circuit currents under different operating conditions, limitations in conventional protection methods, and the need for effective relay coordination, as well as the intelligent protection strategies capable of processing and analyzing large volumes of data, facilitating real-time decision-making and accurate fault detection. The study reviews various intelligent protection schemes implemented in AC, DC, and AC/DC hybrid microgrids, categorizing them based on their decision-making modules, outlining their limitations, and emphasizing potential solutions. The paper provides insights into the protective features, performance evaluation, and applicability of these intelligent methods across different microgrid types.

Pablo Verdugo et al. [15] propose the implementation of a model of a hangar microgrid and its energy management system (EMS) to optimize the dispatch of resources of a thermo-electrical airport grid, using a model predictive control (MPC) approach to address uncertainties, and including a detailed building thermal model, heat pump modeling for the heating and cooling systems, and battery degradation. The proposed mathematical model of the EMS is applied to a model of a microgrid being developed for a hangar at the Waterloo Wellington Flight Centre in Ontario, Canada. Results indicate that the proposed EMS model, featuring multi-room temperature control through multiple thermal resources, can achieve significant CO_2 emission savings of about 60% of yearly operational costs compared to a scenario where the microgrid is not deployed and 5.3% where a single-room building thermal model with a single heat pump is included.

Hui Li et al. [16] present a frequency-secured planning method for virtual inertia suppliers and CHP units in an integrated electricity-heat microgrid. Steady-state models for sector-coupled equipment are developed, specifically CHP units and large-scale heat pumps, for primary frequency response and sizing purposes. Frequency constraints that account for the system inertia of heterogeneous resources are derived and a frequency-constrained planning model constructed. The model balances the power supply, heating supply, and frequency reserves by properly sizing the regulation resources and leverages distributionally robust chance constraints to address wind uncertainty. Case studies conducted on two test systems demonstrate the effectiveness of the proposed method in securing frequency stability while improving the economic performance of IEHM.

Ning Qi et al. [17] deal with long-term energy management of a microgrid coordinating hybrid H_2-BES. An approximate semi-empirical H_2 storage model is developed to accurately capture the power-dependent efficiency of H_2 storage and a prediction-free two-stage coordinated optimization framework, which generates an annual state of charge (SoC) reference for H_2 storage offline. During online operation, it is used to update the SoC reference using kernel regression and make operation decisions based on the proposed adaptive virtual-queue-based online convex optimization algorithm. Numerical studies based on the Elia and North China datasets show that the proposed framework significantly outperforms existing online optimization approaches, reducing operational costs and loss of load by approximately 60% and 90%, respectively, compared to the MPC method.

3. Advanced Computational Methods

The following 14 submissions involved an innovative computational method of some kind.

Qinqin Xia et al. [18] focus on the privacy-preserving operation problem of networked microgrids. A federated deep reinforcement learning-based edge-cloud cooperative architecture is proposed for the cost-effective coordinated operation in which a differentiated private neural network is used for each microgrid agent at the edge, and a global neural network is used at the cloud server to achieve collaborative training. The superior training performance of the proposed framework compared with other related RL methods is validated based on numerical studies on an IEEE 33-bus system.

Muhammad Irfan et al. [19] address the high-frequency fluctuations in microgrids caused by the stochastic nature of RE generation, electric loads, and the presence of electric vehicles. They present a novel enhanced control approach named the particle swarm optimization-trained artificial neural network to optimize the load frequency model of a microgrid with vehicle-to-grid (V2G) integration. Simulation results demonstrate the effectiveness of the proposed method in achieving critical control objectives such as frequency stabilization and load distribution amidst varying degrees of load fluctuations.

Xuesong Xu et al. [20] focus on the distributed energy management of multi-energy microgrids (MEMG) under demand and renewable generation uncertainties. They proposed a hierarchical multi-agent deep reinforcement learning approach for MEMG, in which the inter-MEMG level uses a centralized training decentralized execution framework to achieve the privacy-preserved coordination of MEMG while the intra-MEMG level uses the trust-region model for the multi-agent action control. Numerous case studies demonstrate the effectiveness of the proposed algorithm in reducing energy management costs and carbon emissions and adapting optimization operations as the system structure changes.

Lian-Zhu Shan et al. [21] focus on the DER management of the distribution system. They proposed a generalized Benders decomposition based distributed energy management system for coordinating microgrids in the distribution system, in which a dedicated optimation is proposed to obtain the feasible region of the microgrid operator problem to avoid generating the feasibility cuts during iteration to improve the convergence of the decomposition. Simulations on typical seasonal distribution grid models of China in 2030 verify that compared with the baseline technology, the proposed method resolved more overloading/overvoltage, made more profit, and significantly reduced PV curtailment.

Buddhadeva Sahoo et al. [22] focus on the supervisory control of AC-DC hybrid microgrids that integrate the V2G/grid-to-vehicle VPP. An enhanced supervisory control scheme that combines three sub-controllers is proposed employing a sliding model-based maximum power algorithm, an active current detection technique, and a SoC regulation scheme. Based on the software and real-time hardware-in-the-loop (HiL) simulations, the authors validate the superiority of the proposed method against conventional methods in power management, power quality, and regulatory compliance.

Truong Hoang Bao Huy et al. [23] focus on robust real-time energy management for on-grid H2 refueling stations under uncertainties of energy prices, renewable generation, and H2 demand of FC electric vehicles. They propose a generative adversarial imitation learning based real-time energy scheduling method for statuions, in which the adversarial training involving policy and discriminator networks is used to construct a surrogate neural network of the traditional MILP model for the scheduling of the H2 refueling stations. Extensive simulations on a benchmark refueling stations shows that the learning algorithm increases system profit by 29% compared to the day-ahead MILP strategy.

Jinpeng Qiao et al. [24] focus on the optimal scheduling of an active distribution network (ADN) that integrates a microgrid group and shared energy storage, in which the benefit coordination of multiple entities is considered. They propose a master-slave game schedule strategy to solve the problem of pricing and optimization in multi-entity games, accompanied by a multi-stage distributed iterative algorithm to solve the proposed model. A modified IEEE 33 bus distribution network with three microgrids, one shared storage, two PV units, and one wind turbine is used to test the proposed approach, showing that the power interaction among microgrids decreases the voltage deviation by 8.5% and reduces the network loss by 11.7%.

Jingjing Wang et al. [25] focus high control complexity, output uncertainty, and low RE utilization problems in the integration of distributed resources into an ADN. They proposed a distributed optimization strategy for networked microgrids using network partitioning, including a two-layer optimization model and a synchronous alternating direction method of multipliers algorithm for parallel solution. Case studies show that the proposed strategy reduces dispatch costs by 5.3%, increases PV utilization by 3%, and decreases calculation times significantly compared to centralized control.

Quan Lu et al. [26] tackle the issue of active power imbalance in IEM(S) due to the integration of distributed RE sources, which causes frequency deviations and increased operational costs. They introduce a decomposition prediction fractional-order active disturbance rejection control deep Q network that integrates modal decomposition, fractional-order active disturbance rejection control, and deep Q network to manage generator control and mitigate frequency fluctuations. Simulation results demonstrate that the proposed control strategy significantly outperforms traditional and existing control methods at reducing frequency deviation, generation cost, and carbon emissions, while enhancing the stability and economic efficiency.

Lei Dong et al. [27] focus on the coordinated active and reactive power optimization of multi-microgrids connected to distribution networks. They propose a data-driven method based on a multi-agent deep reinforcement learning algorithm to address the challenges caused by uncertainty and nonconvexity, in which an attention mechanism is introduced to improve the convergence performance in a high-dimensional state-action scenario. The superiority of the proposed method compared to the traditional methods in terms of convergence speed, convergence effect, scalability, and response to RE fluctuation is verified on a modified IEEE 33-bus distribution network with nine microgrids.

Md. Mhamud Hussen Sifat et al. [28] create a digital twin of the microgrid to optimize power generation, highlighting the computational efficiency and self-healing control. In their digital twin (DT), they adopt a polynomial regression algorithm to model the microgrid, use the gradient descent algorithm to solve the optimization problem, and implement the logistic regression algorithm for self-healing control. They verify the performance of the DT system using an islanded microgrid with DC and AC loads, in which the grid performance, uncertainty handling, and DT-controlled optimized operations are tested and verified.

Wenfa Kang et al. [29] focus on distributed optimal power management of smart homes with network and communication constraints. They proposed a privacy-aware distributed weighted optimization algorithm with a dynamic event-triggered communication mechanism that avoids Zeno behavior for this problem, for which four theorems were proposed to show that the proposed optimization algorithms can solve the economic power dispatching when the network constraints and denial-of-service attacks are considered. Simulation results based on different cases validate the effectiveness of the proposed methods.

Yuanxing Xia et al. [30] focus on prosumer bidding behavior in a peer to peer (P2P) energy market, given their loads and resources. They propose a virtual SoC-dependent bidding strategy to accommodate battery parameter changes and market opportunity costs, accompanied by a virtual storage modeling method and an alternating direction method of multipliers distributed market equilibrium. Two simulated cases verify the proposed method can accommodate prosumer parameter changes and trading preferences, reducing opportunity costs 41.2% when allowing prosumers to bid differently in various virtual SoCs.

Xiao-Yan Zhang et al. [31] focus on the cooperative scheduling of H2-based community microgrids, which consider the refueling preferences of H2 vehicles and industrial H2 demand. They propose an end-user-oriented transactive energy framework to synergize the H2 and electricity sharing process within the microgrid, which is modeled as an energy density-weighted asymmetric Nash bargaining model and then solved by an adaptive alternating direction method (ADM) of multipliers. Finally, the performance of the proposed method is verified on hypothetical systems, which improves the convergence speed by 66.13% on a system involving 50 prosumers and 50 H2 vehicles and reduces the social costs by 50.3% in a smaller-scale system consisting of 5 prosumers, 5 H2 vehicles, and 1 industrial H2 user.

4. **Operations and Control**

The following 14 papers examine new and traditional control topics.

Shenglin Li et al. [32] present a multi-timescale energy management system, comprising a day-ahead economic dispatch that considers grid, operating and maintenance emission costs, and intra-day rolling correction. The proposed system also considers a dynamic operating reserve and demand participation that aids in limiting the fluctuations on the grid connection. While the proposed scheduling scheme is able to reduce the peak-to-valley fluctuations by 62%, the multi-scale EMS reduces the operating cost by approximately 2.5%.

Chenghao Lyu et al. [33] develop a two-layer co-optimization strategy for microgrid design. While the inner layer comprises an EMS based on a rolling horizon strategy, the outer layer handles the sizing of the microgrid through an optimization problem solved by particle swarm optimization algorithm. The proposal reduces overall cost when compared to other SotA techniques (e.g. a reduction of total cost of 4.6% when compared to other two-layer methods) while achieving a more extensive coverage of the solution space.

Rufeng Zhang et al. [34] introduce a two-stage robust optimization method for a multi-energy microgrid that comprises power-to-H2-and-heat conversion, among other sources. The day-ahead upper stage is solved by a column-and-constraint generation algorithm, while the real-time lower level stage is solved by an algorithm that uses Karush-Kuhn-Tucker (KKT) conditions and big-M. Although the day-ahead cost increases, the proposed robust optimization method reduces real-time operating costs by up to 13.7%, improving over SotA deterministic and stochastic approaches.

Sen Zhang et al. [35] also present a two-stage robust optimization method focused on the low-carbon operation of distributed energy systems. The day-ahead master problem is solved by an ADM method combined with the column-and-constraint generation algorithm. The real-time slave problem is treated as a single-layer problem thanks to the introduction of KKT conditions. Through several scenarios of a case study, the authors show reductions of 7.86% in cost and 8.18% in emissions when compared to a deterministic operation.

Cheng Zhong et al. [36] propose an MPC for secondary frequency regulation of PV distributed generators coupled through converters acting as virtual synchronous generators. The MPC uses rolling optimization through a two-layer moving horizon estimation, for both local state variables of the virtual synchronous generators and centralized level state variables. The proposed secondary controller performs better than SotA alternatives such as Kalman filter and fully centralized MPC, with up to 86% lower root mean square error.

Jinshuo Su et al. [37] contribute to the SotA through a distributed secondary control proposal for islanded microgrids, for both voltage and frequency, based on Lyapunov functions. The control strategy uses feedback information from phasor measurement units at the distribution level, and controller gains are chosen to ensure stability through the Lyapunov stability condition. The proposed secondary control scheme is tested on a modified IEEE 34-bus system and demonstrates better dynamic performance, reaching a 26% reduction of overshoots and 64% faster dynamics when compared to an alternative distributed controller.

Shaoping Chang et al. [38] present a novel distributed secondary controller for DC microgrids that ensure an adjustable fixed time for convergence. The proposal uses a directed communication topology and interacts with low-level droop control. The authors also prove that the proposed controller is Lyapunov stable. The proposed controller is validated on a HiL real time simulation setup, demonstrating voltage regulation and current sharing.

Hammad Armghan et al. [39] propose a tri-layer control for a microgrid cluster interfaced with a shared H2 energy storage system. The lower layer performs primary control through a modified super twisting sliding mode control. The middle layer performs secondary control through an EMS whose objective is to minimize operating cost and emissions. The upper layer provides tertiary control by an optimal operation of the H2 sharing scheme among microgrids. The proposed tri-layer control was validated through simulation and verified on a HiL environment, reducing the carbon intensity to 13.8% of that of a microgrid cluster without coordination among microgrids, while maintaining a tracking accuracy of 99.984% at the primary level.

Nsilulu T Mbungu at al. [40] present an energy coordination control scheme for grid-tied microgrids that include smart home technologies, RE and storage. The proposed scheme allows for an open-loop, closed-loop or MPC-based EMS. The coordination control es evaluated through a series of economic, environmental and operational key performance indicators. The results demonstrate that each EMS variant provides better performance on selected indicators, with a more robust result for the MPC variant. Energy savings are as high as 36%, while maintaining good voltage regulation and minimal losses.

Haochen Hua et al. [41] propose a centralized dispatch strategy for multiple interconnected IESs, considering electricity and heat, and modeling complex energy flows and interactions. The authors incorporate an aggregated DR mechanism used between a centralized operator and the interconnected IESs. To preserve information privacy and aid in distributed problem solving, an adaptive step size regularized ADM is used. The proposed control strategy is evaluated on a 10-IES system through a series of scenarios that include IESs with and without interconnection. The use of aggregated DR provides reductions of IES daily costs of about 1.5%, while increasing the profit of the operator by more than 2%.

Hao Li et al. [42] contribute to the SotA with a distributed secondary voltage control scheme that ensures a predefined time convergence. The proposal includes privacy of voltage and reactive power information through the incorporation of a privacy-preserving distributed average estimator. The proposed control is validated on a HiL simulation setup that models a 4-inverter islanded AC microgrid. The results show the correct operation of the controller with convergence time of as low as 0.3s, and better consensus and privacy preservation than alternative distributed voltage controllers, while maintaining correct reactive power sharing.

Wenfa Kang et al. [43] propose a distributed event-triggered voltage control algorithm that considers communication delays. The controller coordinates a virtual energy storage system (ESS, batteries and flexible loads) at the primary and secondary control level. Through the design of feedback controllers and establishing practical limits for the feedback control gains, the authors demonstrate practical implementation of the controller for arbitrary, varying delays. The proposed control scheme is validated through simulation, showing its compliance with voltage standards and with better performance when compared against other SotA methods.

Lifu Ding et al. [44] contribute to the SotA through a novel fault diagnostic method for microgrid clusters. The proposed method uses Message Passing Neural Networks for the fault diagnosis, and Graph Lasso for topology identification. The algorithms are supported by a DT that uses transient simulation models, cloud- and edge-artificial-intelligence models. The method is validated using data from a real 3-microgrid cluster in Guigang, China. The results show 99% accuracy for fault line localization and 97% fault type recognition.

Quanpeng Lv et al. [45] propose a novel robust scheduling method for low carbon factories that incorporate captive power plants. The scheduling is based on a two-stage robust optimization model and manages both industrial production and energy generation while ensuring carbon quotas. The two-stage model is solved by a parametric column and constraint generation algorithm, along with the use of KKT conditions for making each stage a single-level optimization problem. The proposed scheduling method is validated through a case study comprising the operation of a 3-production-line factory over a week. The results show that, although the costs may increase on the integrated production and energy scheduling, the impacts of uncertainties can be mitigated.

5. Reliability and Resilience

Reliability and resilience are topics always closely related to microgrids, and 14 papers roughly addressed these related issues.

Can Wang et al. [46] introduce a two-stage underfrequency load shedding strategy designed for microgrid groups. The first stage addresses rapid frequency drops, considering load frequency and voltage characteristics, while the second stage optimizes shedding based on conditional value at risk theory to minimize risks from load uncertainty. Tested on the IEEE-37 node microgrid model, the strategy effectively reduces frequency fluctuations and economic losses, outperforming other approaches by achieving optimal load shedding ratios that enhance system stability.

Xia Zhao et al. [47] present an adaptive robust optimization method to quantify the flexibility of seawater desalination plants in DR. The methodology defines technical and economic flexibility intervals, using two adaptive robust optimization models with a nested column and constraint generation algorithm. When applied to reverse osmosis desalination plants, it reduces DR execution deviations from 122 kWh to zero and achieves over 20% cost savings, while optimizing plant participation in DR and enhancing interaction with power distribution systems.

Yicun Chen et al. [48] develop a cascading failure propagation model for complex networks with a node emergency recovery function. This model simulates cascading failures in networks like power grids and water systems, incorporating a recovery mechanism that allows nodes to restore functionality probabilistically. Simulations show that increasing the node recovery probability decreases the network failure risk by 53.1% when raised from 0 to 1/2, providing valuable insights for improving the resilience of critical infrastructure networks.

Antonio Enrique González Reina et al. [49] outline a cooperative MPC framework to enhance energy resilience in networked microgrids. By optimizing energy surplus and integrating hybrid energy storage systems, including batteries and H2, the framework minimizes operational costs while maintaining power supply to critical loads. Numerical simulations demonstrate significant improvements, reducing failure risks and ensuring system autonomy during disruptions, balancing cost efficiency with resilience.

Yang Li, et al. [50] propose an innovative model-free resilience scheduling method based on state-adversarial deep reinforcement learning for integrated DR enabled EMS, which face challenges from RE and load uncertainty, as well as the increasing impact of cyber-attacks. The proposed method uses an integrated DR program to explore the interaction of electricity-gas-heat flexible loads and applies a state-adversarial Markov decision process model characterizes the energy scheduling problem of an IEM(S) under cyber-attack. Simulation results demonstrate the method adequately addresses the uncertainties mitigating the impact of cyber-attacks on the scheduling strategy and ensuring stable supply. Compared to the original soft actor–critic algorithm, a 10% improvement in economic performance is achieved under cyber-attacks.

Melissa Eklund et al. [51] propose a multi-criteria decision analysis framework integrating social capital with business models for community microgrids. This approach evaluates and selects context-sensitive business models for local energy markets, focusing on components such as ownership, pricing, and value propositions. A case study highlights the framework's ability to optimize business model selection by aligning technical and operational factors with community socio-economic contexts, enhancing microgrid resilience and social integration.

T Ide et al. [52] analyze synchronous instabilities in IBRs within microgrids, developing a mathematical model that incorporates transmission lines and inverter control systems. Focusing on grid-following and grid-forming inverters, the study uses eigenvalue sensitivity analysis to identify control parameters influencing sub-synchronous oscillations. Simulations in a microgrid with 83% IBRs show that adjusting the reactive power-voltage droop coefficient suppresses oscillations at around 1.6 Hz.

Zafar Ayub Ansari et al. [53] present a fractional-order proportional-integral cascaded with one plus tilt-derivative (PIλ-(1+TD)) controller, optimized using a flow direction algorithm for frequency regulation in a seaport hybrid microgrid. Including biodiesel generators, FCs, and energy storage systems, the controller reduces settling time by 30%-38%, undershoot by 16%-27%, and overshoot by 76%-87% compared to proportional integral derivative and fractional order proportional integral derivative (FOPID) controllers, improving dynamic stability and resilience.

Armando J Taveras-Cruz et al. [54] presents a comprehensive review of adaptive protection for AC microgrids based on multi-agent systems. It highlights the challenges of bidirectional power flow, voltage/frequency dynamics, and reduced fault current capacity, which complicate protection schemes. The multi-agent-based approach offers high autonomy, fault tolerance, and robustness across different microgrid topologies. The paper systematically explores design frameworks, development tools, and real-time implementation challenges. It identifies limitations, such as the need for real-world application, cybersecurity risks, and communication infrastructure requirements, proposing future research directions to address these gaps.

Nima Khosravi et al. [55] introduce a two-layer operational scheme for managing voltage-frequency stability in distributed energy systems. By employing a hierarchical deep-learning-based recurrent convolutional neural network, the method optimizes voltage-frequency control and enhances microgrid resilience. Voltage fluctuations are reduced to 0.002 pu with this neural network, compared to 0.126 pu for FOPID controllers, demonstrating significant improvements in stability, control accuracy, and adaptability to varying load conditions.

Wiam Ayrir et al. [56] propose a modular approach for optimizing interconnected microgrids using reconfiguration-based techniques. The method employs metaheuristic algorithms like the slime mould algorithm and artificial hummingbird algorithm (AHA) to identify optimal tie switches, improving power distribution networks. Simulations on two 33-bus systems show that vertical interconnection reduces power losses by over 39% and improves voltage magnitude to 0.9481 pu.

Yongpan Chen et al. [57] introduce a hierarchical distributed control for DC microgrid clusters to balance autonomy and cooperation among microgrids. The proposed method achieves proportional current sharing and voltage regulation under both autonomous and cooperative modes. A novel stability analysis based on Padé approximation identifies the key link limiting the time delay margin, enhanced by a scattering transformation, which improves the time delay margin from 23.2 ms to 275 ms, verified via HiL and MATLAB simulations. This approach significantly enhances delay tolerance and system scalability in large-scale clusters.

Shunbo Lei et al. [58] present a deep reinforcement learning based approach for sequential service restoration in microgrids. The method leverages grid-interactive flexibility from air conditioning systems and addresses both endogenous and exogenous uncertainties. By modeling the microgrid restoration problem as a markov decision process and using a twin delayed deep deterministic policy gradient algorithm, the approach optimizes power supply stability and resilience, validated on IEEE 33-node and 123-node systems.

Jiawei Wang et al. [59] propose a resilient energy management framework for building-level multi-energy systems connected to low-temperature district heating. Using a proximal policy optimization algorithm, it optimizes operational costs under contingencies, addressing uncertainties in electricity and heating demands. The approach achieves a 13.7% cost reduction compared to traditional model-based methods, while enabling real-time control within milliseconds. Applied to a Danish residential building, the framework effectively integrates heating and electrical systems, minimizing energy disruptions and enhancing cost-efficiency.

6. **Markets, Trading and Economics**

A total of 15 articles contribute to the area of Markets, Trading, & Economics. Several of these contributions address the area of primary and secondary regulation of microgrids, including works in both AC and DC microgrids.

Yunfeng Ma et al. [60] specify a secondary flexibility market in the power sector among high proportional behind-the-meter RE resources. The market allows players to submit an empirical load curve to the market organizer. During the clearing stage, a social welfare equilibrium problem is solved, and the equilibrium trading volume can be adjusted in the collation stage to account for the distribution network voltage magnitude balance. Finally, a response schedule strategy is designed to analyze the behaviors of the players. The results have shown significant cost reductions for players with sufficient flexibility.

Zehua Zhao et al. [61] propose a personalized P2P energy trading system to explore the role of the participants' Socio-Demographic Characteristics in the decision-making process. The system periodically collects the participants' bids and pair energy sellers and buyers to form transactions where an attention-based characteristic inference system is developed to identify the participants characteristics from the on-site historical smart meter readings. The system analyzes the importance of energy buyers' demands based on their characteristics, and an alternative current network constrained P2P energy market clearing model is formulated to maximize the participant population's social warfare by considering their energy demand importance and economic benefits.

João Soares et al. [62] carry out a comprehensive review on fairness in local energy systems by thoroughly analyzing 80 scholarly papers. The main objectives of this review are twofold: to provide a definition of fairness within this domain and to examine how this concept is currently shaped and interpreted. The analyzed studies are categorized according to their applicability to local systems, fairness and justice interpretation (e.g., equality, meritocracy), and use of post-method indicators to evaluate fairness performance. The work explores the identified gaps in the existing literature and outlines guidelines and prospective research directions for future studies addressing fairness issues.

Xin Liu et al. [63] introduce a multi‑leader single-follower Nash-Stackelberg game model that is designed to facilitate the optimal aggregation of DER agents in a competitive distribution-level market involving multiple players. In the optimization modeling, the DER agents function as leaders, formulating their bidding strategies to maximize profits. Conversely, the VPP acts as a follower, responsible for performing market clearing. The distributed locational marginal price derived from this process serves as the settlement basis for DERs. This model offers an expanded set of Nash equilibrium solutions for VPPs, enabling the selection of suitable aggregation schemes tailored to practical requirements.

Ling-Ling Li et al. [64] propose a multi-objective optimization model for a microgrid energy management system considering the cost of the energy storage system degradation and carbon trading. The multi-objective optimization is solved by an AHA. The simulation results demonstrate that the proposed strategy has 20.2% lower total operating costs, 4.5% lower carbon emissions, and 32.6% longer battery life than the conventional microgrid system, which is critical for improving the operation stability, economy, and carbon footprint of the system, and extending the service life of the battery at the same time.

Andrew Xavier Raj Irudayaraj et al. [65] build a P2P energy transaction platform utilizing proof of Authority based Ethereum blockchain. A federated average learning of recurrent zeroing neural dynamics designed self-adaptive fractional-order proportional integral derivative controller is proposed for distributed frequency control of networked microgrid (NMG) systems. The blockchain implementation ensures that the transfer of signals remains secure from cyber threats. The established blockchain network using Raspberry Pi devices are connected to the network in OPAL-RT through the socket interface and communicate via TCP/IP protocol.

Wei Liao et al. [66] conduct a comparative study on electricity transactions between multi-microgrids comprising heterogeneous building communities considering EVs, utilizing a hybrid game theory-based P2P electricity trading paradigm and a traditional TOU strategy under the peer-to-grid peer to grid (P2G) paradigm. Through a comprehensive analysis, considering the dynamic electricity demand and technoeconomic factors, simulation results demonstrate that the hybrid game theory-based P2P paradigm offers significant advantages over the traditional TOU strategy under the P2G paradigm. Meanwhile, utilizing EVs and flexible loads as energy flexibility assets further enhances the system's flexibility and responsiveness to demand fluctuations.

Yi Yan et al. [67] specify a market participation method for a multi-layer integrated community energy system that considers multiple types of independent energy participants. The study provides a reliable tool for solving the complex model of multiple participants, it also improved the status of market and enthusiasm of dispatching for energy storage, users etc., and broke the monopoly structure of energy seller side market participation. The simulation results have demonstrated improvements on effective utilization rate of energy storage, energy response of users and the total revenue of the energy purchasing side.

Cairong Song et al. [68] develop a multi-energy load forecast method using a hierarchical multi-task learning task, resolved by using a spatiotemporal attention mechanism and a gated temporal convolutional network. The coupling relationships between different energy sources are analyzed both qualitatively and quantitatively to identify the coupling relationships between different energy loads and to distinguish relevance factors on loads. Moreover, a gated temporal convolutional network with hierarchical structure is devised to achieve multi-task learning. The proposed method has demonstrated advantages on reducing the mean absolute percentage error in multi-energy load forecasting and demand-side management.

Asmita Ajay Rathod et al. [69] use a hybrid PV/wind/battery/diesel generator/power to H2 system configuration incorporating technical parameters: loss of power supply probability, PV fraction, and wind fraction; as well as economic factors; cost of energy, net present cost, and annualized system cost; plus the social Human Development Index. An Improved Red-Tailed Hawk Algorithm is utilized that incorporates nonlinear decay and chaotic map strategy for designing optimum hybrid systems. The appropriate size and a techno-socio-enviro-financial evaluation of a hybrid off-grid RE system are presented. The algorithm demonstrates superior performance in mitigating CO2.

Chenghao Lyu et al. [70] develop a co-optimization method that can balance economic and frequency regulation performance. The simulation results of co-optimization reveal the impacts of RE systems and ESSs through Pareto front analysis. A comparative analysis with the current policy approach showcases the risks of obtaining suboptimal solutions under existing policies. Some radical policy settings result in a dissatisfaction rate larger than 100%. This study elucidates the role of co-optimization by advancing comprehension of the impacts of RE systems and ESS while providing a method to achieve the appropriate trade-off.

Qinghan Wang et al. [71] propose a Stackelberg-equilibrium-based optimization approach for solving the collaborative charging management problem of EVs and H2 vehicles among the vehicle fleet aggregator, the distribution system operator (DSO) and the H2 system operator in a regional integrated electricity‑H2 system. The impacts of the distribution locational marginal price profiles of electricity and H2, as well as the penetration of EV-HV and electrolysis are considered. The proposed strategy not only enables regional collaborative charging management of EVs and HVs and electricity‑H2 dispatch; but also leads to a reduction in energy cost for the fleet aggregator and alleviates operating power congestion.

Cláudio AC Cambambi et al. [72] build a hierarchical energy management system that can minimize operational costs and maximize individual benefits of multiple geolocated microgrids. A coalition formation algorithm is developed to optimize energy exchanges between geolocated microgrids, leading to a significant reduction in costs. The highest percentage reductions in losses (52.63% to 71.53%) in the cooperative state compared to the non-cooperative state, indicating significant cost savings. The effectiveness of coalitions in reducing losses and operational costs is demonstrated, emphasizing the importance of flexible approaches in addressing challenges such as geolocation and variable weather conditions.

Suijie Liu et al. [73] propose a techno-economic impact evaluation method utilizing matching index and net present value (NPV) of various hybrid RE sources combined with three different integrated building energy-sharing systems via instantaneous and predictive microgrid-based and local electric EV-based energy-sharing. The research results demonstrate that with integration of instantaneous microgrid-based and local EV-based energy-sharing systems, the index improved by 7.19% and 6.86%, NPV improved by 9.53% and 5.70%, respectively, while specific cases show various improvement outcomes largely related to the types of renewable combinations. Under instantaneous micro-grid-based sharing, the divergency of two buildings' renewable combinations brings at most 33.59% technical improvement and 3,764,380 HKD economic benefits. In contrast, the similarity of both renewable combinations helps achieve a maximum 12.02% matching enhancement and an extra 866,690 HKD NPV improvement under local EV-based energy-sharing.

Jonathan Lersch et al. [74] develop a sequential modeling approach to study the integration of energy sharing schemes facilitated by RE communities and their impacts on grid performance, including component loading, voltage magnitudes, and grid reinforcement costs. Twelve scenarios reflecting different RE community configurations, DER adoption levels, and pricing strategies for both current (2023) and future (2037) contexts in Germany are investigated to indicate that implementing energy sharing not only results in considerable cost savings at the community level but also brings significant reductions in grid asset loading.

7. Applications and Demonstrations

Few papers focus directly on specific applications or demonstrations, but the following 11 do include such an element.

BALM Hermans et al. [75] address the problem of increasing variability on both the supply and demand sides of grids. The authors demonstrate the optimal model-based local balancing control of an office microgrid with 174 charging stations, local PV generation, and stationary batteries, but without vehicle charge control. The system functioned for 3 weeks, achieving an average daily peak power reduction of 59%.

Yu Su et al. [76] consider the dynamic operation of microgrids with flexible boundaries considering unbalanced networks and loads. Two types of relaxations for the power flow equations in radial networks are assessed and combined with the binary switching variables. The optimal operation problem is formulated as a MILP and a mixed-integer semidefinite program (MISDP). Updates required for the case of multiple grid-forming sources in the dynamic boundary microgrid and bi-directional power flow are also introduced. Case studies in the IEEE 13 bus test system and a networked microgrid in Ajuntos, Puerto Rico, show significantly improved resiliency.

Nianyuan Wu et al. [77] note that interest in energy conservation and emissions have led to a series of regulations by the International Maritime Organization, while mechanisms for whole ship optimization are unclear. This paper constructs a technical selection, capacity allocation, and operational optimization model using MILP. The economic optimization results show that the net present cost of ship energy systems can be reduced by 20%, while the NOx, SOx and CO2 emissions of the system are reduced by 41%, 20% and 32%, while the energy efficiency of the optimized ship energy system is improved by 9% compared to a conventional ship energy system.

Jiarui Zhang et al. [78] introduce R-CELLS, which are net-zero 146 m^2 cold climate single-story residential buildings conceived and constructed by Team Tianjin U+ for the Solar Decathlon China 2022. The R-CELLS energy system integrates various RE sources (thermal and building integrated PV, plus wind turbines); furthermore, it incorporates multiple energy storage systems, batteries, a hot water tank, and phase change material. A hybrid AC and DC electrical system with three voltage levels is used. Simulation suggests an annual energy consumption of approximately 54.0 kWh/m2/yr. Due to differences between competition conditions and the designed conditions, the total power generation fell by 9.74% below expectations, while the total energy consumption exceeded them by 62.89%, but periodic off-grid operation was demonstrated.

Md Morshed Alam et al. [79] propose a comprehensive analysis approach for transforming existing low-voltage networks into microgrids. A data-driven machine learning-based clustering and profiling approach is designed and implemented to extract the data, constraints, and dependencies from historical data, and a comprehensive analysis is carried out utilizing real historical demand and generation data of an energy community in Australia. The proposed microgrids achieve higher renewable RE utilization and lower electricity costs compared to grid-connected systems, potentially reducing carbon emissions by up to 98% when transitioning from coal-based grid systems to the proposed microgrid system. A transformation from a grid TOU tariff-based system to the proposed microgrid setup can lead to a cost reduction of 65%.

Xuehua Xie et al. [80] tackle the optimization of multi-community integrated energy systems to strategically harness energy-carbon synergy advantages within these systems. The authors propose an individualized adaptive distributed approach for energy-carbon coordination with power transformers. Simulation results show that the proposed scheduling model can effectively guarantee the safe operation of power transformers and achieve higher economic and environmental benefits than a reference one that ignores energy-carbon coordination.

Baligen Talihati et al. [81] address the role of BES systems in ensuring the reliable operation focusing on spreading out BES costs by energy sharing between multi-entities. A consistent evaluation framework across use scenarios can optimize the BES operational efficiency and profitability, which is validated by multiple representative use scenarios. Community Energy Storage Sharing stands out with the lowest operational cost, while incurring the lowest capital cost.

Muhammad Abuelhamda and Claudio A Cañizares [82] address the possibility of developing integrated electricity and district heating systems in cold remote communities. A dynamic model to distribution of distributed generator waste heat and includes frequency control. An example winter day application at the Kasabonika Lake First Nation in northern Ontario with a mix of diesel and renewable sources is executed. Heat pumps provide additional heat, when needed, and deliver additional frequency response. Multiple case studies demonstrate the relative efficacy of microgrid components to control frequency.

Zhuoli Zhao et al. [83] aim to realize reliable online energy coordination for multi-stakeholder IEMs, and propose a novel robust dynamic dispatch framework for a diverse stakeholder IEM based on enhanced hierarchical MPC. At the upper level, the data-driven MPC strategy enables the integrated energy operator to optimize the schedules of energy generation and supply. At the lower level, the standard rolling. An MPC strategy is introduced for the multi-load demand aggregator to improve response performance. This hierarchical equilibrium problem can be reformulated as a single-level MPC-based multi-layer MILP based on the multi-period KKT optimality conditions and the strong duality theory. Comparison studies demonstrate the proposed enhanced hierarchical MPC method can obtain an excellent balanced scheduling scheme between robustness and economy.

Edvin Wallander et al. [84] address the problem of increasing electrification of agriculture using a new model capable of simulating electric non-road heavy machinery systems with a local grid-connected energy management system and two on-field energy replenishment modes: on-field battery exchange and charging. The agent-based model is configured with real-world weather, geographical, and operational data collected from two participating Swedish farms. Model planning algorithms modify agent behavior to synchronize activities. Two Swedish case studies are conducted, simulating full electric field operation. The results show that performing fieldwork requires only 5% more time than a diesel-driven machine system baseline while consuming just 37.5% of the energy. The effects of different battery sizes, grid connection power levels, and energy replenishing modes are explored, and the impact on the total process effectiveness and electrical system load is shown.

Jinpeng Qiao et al. [85] propose a trilayer Stackelberg game schedule strategy for an ADN based on shared storage. In the upper-layer, the DSO can be the leader to determine the trading price considering the power demand of the middle and lower layers, which can realize safe operation, peak shaving, and valley filling. In the middle-layer, a shared energy storage operator can serve both as the leader to formulate the leasing price and as the follower to respond the trading price, and in the lower-layer, a microgrid coalition serves as the follower to formulate leasing capacity and to respond the trading price. To solve the trilayer SG model effectively, the existence and uniqueness of the equilibrium solution can be proved by taking advantage of the multi-step backward induction method. Then, a distributed nested iterative algorithm is further exploited to avoid the possible oscillation in iterative optimization. Finally, the effectiveness and rationality of the proposed schedule strategy is verified using the IEEE 33 bus system.

8. Conclusion

This VSI shows that interest in microgrids remains high worldwide, as they are mature from special case paradigms to offer viable solutions to the challenges of increasing RE penetration, remote electrification, reliability and resilience, energy independence, etc. It's fair to say microgrids are now a central element in the conventional vision for our future power delivery system. Ongoing research continues to focus on improving the basics, microgrid design, management, and control. Multi-energy microgrids offers a promising area, and naturally, the application of artificial intelligence is storming into the field. Despite impressive progress, research and innovation in microgrids still has many open technical issues to cover, but additionally exploration of business cases and social issues, links to energy communities, and multi-microgrid cooperation remain fertile topics. Particularly, microgrids are considered the technical basis for energy communities.

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11. Abbreviations and Acronyms

AC	alternating current
ADM	alternating direction method (multiplier)
ADN	active distribution network
AHA	artificial hummingbird algorithm
BES	battery energy storage
CHP	combined heat and power
CO2	carbon dioxide
DC	direct current
DER	distributed energy resource(s)
DR	demand response
DSO	distribution system operator
DT	digital twin
EMS	energy management system
ESS	energy storage systems
FC	fuel cells
FOPID	fractional order proportional integral derivative
GAMS	General Algebraic Modeling System
H2	hydrogen
HiL	hardware-in-the-loop
HKD	Hong Kong Dollar
IEM(S)	integrated energy microgrid (system)
IoT	internet of things
KKT	Karush-Kuhn-Tucker
MATLAB	MATrix LABoratory (high level language for numerical computing)
MEMG	multi-energy microgrids
MI(LP)	mixed integer linear program
MPC	model predictive control
NOx	oxides of nitrogren (NO + NO2)
NPV	net present value
OPAL-RT	OPAL-RT Technologies Company
P2G	peer-to-grid
P2P	peer-to-peer
PV	photovoltaic
RE	renewable energy
SoC	state of charge
SotA	state of the art
SOx	oxides of sulfur
TOU	time-of-use
V2G	vehicle-to-grid

VPP	virtual power plant
VSI	virtual special issue

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